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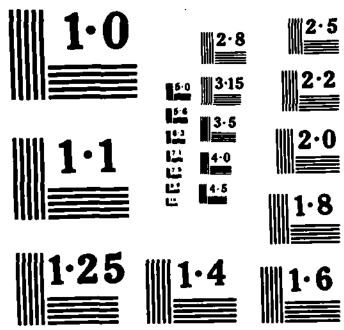

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FEASIBILITY STUDY OF RADAR-TRANSMITTING MATERIALS

FINAL TECHNICAL REPORT, 15 MARCH 1985

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FINAL TECHNICAL REPORT RNASCHQ8401

M. SPARKS

15 MARCH, 1985

PREPARED FOR

NAVAL AIR SYSTEMS COMMAND HEADQUARTERS

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CONTENTS

ABSTRACT

It is shown that it is unlikely that the principles that were originally identified for investigation in this study can be used to obtain a practical material having high microwave transmittance. Electron plasmas in solids are too highly damped at room temperature to give high transmittance. Low-frequency phonon modes conceivably could have frequencies in the microwave region, but the frequency at which the refractive index is equal to one would still be in the infrared region, not the microwave region. After the research on the program was completed, it was suggested that the possibility of attaining high microwave transmittance in ionic conductors should be considered. Although there was no time for such a study, a brief investigation indicated that some ionic conductors possibly could be able to provide high microwave transmittance. They should be studied further.

I. INTRODUCTION

The purpose of this program is to detemine the feasibility of attaining microwave-transmitting materials by making the real part n_r of the refractive index of the materials equal to one

$$n_r = 1. \tag{1.1}$$

A useful application is to obtain low microwave reflectance by attaining high transmittance. In this case the surface transmittance -- that is, the transmittance into the material, not necessarily the transmitance through the material -- is of primary interest. In fact, in some applications, a high surface transmittance is desirable in order to obtain low reflectance and a low transmittance through the material is desirable in order to reduce reflections from components behind the material (which could increase the overall reflectance). In this case the absorptance, or the imaginary part of the dielectric constant, should be sufficiently great to absorb the microwave energy, but not sufficiently great to cause a sufficient impedance mismatch at the surface to make the reflectance great.

Barrett[1] suggested the investigation of obtaining high microwave transmittance by using surface electron plasmas. Since the resonant frequencies of these modes are in the ultraviolet region, rather than in the microwave region, we suggested using low density electron plasmas in dielectric materials. Murday[2] carried out such an investigation in parallel with the present one. We also suggested other systems that could

give rise to $n_r = 1$ at some frequency in the microwave or millimeter regions.

Murday's central result -- that the electron relaxation frequencies are so high that electron plasmas in dielectric materials do not give rise to high transmittance -- is in agreement with our result on electron plasmas. Neither Murday's investigation nor the present one considered electron plasmas in alkali halides. Even if high transmittance were attained in these marterials, their poor physical properties would rendered them useless in applications of current interest. Murday did not consider phonons, ionic plasmas, or the other phenomena discussed in Sec. VIII.

It is shown that it is unlikely that the principles that were originally identified for investigation in this study can be used to obtain a practical material having high microwave transmittance. Electron plasmas in solids are too highly damped at room temperature to give high transmittance. Low-frequency phonon modes conceivably could have frequencies in the microwave region, but the frequency at which the refractive index is equal to one will still be in the infrared region, not the microwave region. Near the end of the program we were asked to predict whether high microwave transmittance could be attained in ionic conductors. Although there was not sufficient time to complete such a study, preliminary results indicate that ionic conductors should be marginally able to provide high microwave transmittance. They should be studied further.

The proposed method is based on the key result from the technology base that the transmittance of a material that exibits a resonance to radiation can approach one over a narrow frequency range near the

resonance-absorption peak, as discussed below. The first phase of the investigation is to determine the feasibility of attaining high transmittance. The second phase is to examine methods of tuning the frequency at which the high transmittance occurs.

The central features of the underlying physics are as follows: The index of refraction

$$n = n_r + i\kappa, \tag{1.2}$$

is the optical property of practical interest because it determines the electromagnetic propagation. The mode amplitude, such as the electric field E, is

$$E \sim \exp(ink_0z) = \exp(in_rk_0z)\exp(-i\kappa k_0z), \tag{1.3}$$

where $k_0 = 2\pi/\lambda$, λ is the vacuum wavelength and z is the distance along the propagation direction. Equation (1.3) shows that n_r determines the wavelength (λ/n_r) in the medium and κ determines the exponential decay of the propagating mode.

In calculating the refractive index, it is usually convenient to consider the dielectric constant

$$\varepsilon = \varepsilon_r + i\varepsilon_i. \tag{1.4}$$

Expressions relating n_r and κ to ε_r, and ε_i are given in Sec. II. Expresions for ε_r, ε_i, n_r and κ for plasmas and phonons are given in Secs.

III and IV.

It is possible to have the real part of the refractive index n_r equal to one at some frequency for some materials. At this frequency, the impedance of the material is matched to that of air. Thus, the transmittance is one at this frequency. In practice, the transmittance is less than one for a number of practical reasons, including losses and inhomogeneities in the material. The frequency at which $n_r = 1$ is sometimes called the Christensen frequency because Christensen used the effect in a bandpass filter.

There are a number of possible physical mechanisms that can give rise to the real part of the refractive index, n_r, equal to one. Usually $n_r = 1$ occurs as a result of the dispersion in the refractive index near a resonance absorption, such as that of the longitudinal-optical (Reststrahlen) phonon or a plasmon.

For example, the real and imaginary parts of the refractive index of a typical solid associated with the resonance absorption of the transverse-optical phonon are shown in Fig. 1. The real part n_r is equal to one at two frequencies, both above the resonance frequency ω_0. The damping loss is lower at the greater of the two frequencies because this frequency is further from the absorption resonance at ω_0.

The specific goals of the program are as follows:

o In general determine the feasibility of the proposed method of obtaining microwave-transmitting materials.

o Investigate the possibility of using low-frequency plasmon modes and low-frequence phonon modes to obtain a real part of the index of refraction

equal to unity.

o Estimate the width of the frequency region over which the high transmittance occurs.

o Study the effects of mode attenuation on the trannittance.

o Study the possibility of using a material containing both low-frequency plasmon modes and low-frequency phonon modes to obtain a tunable microwave-transmitting material.

o Verify that the low-probability methods of obtaining microwave transmitting materials that are discussed in Sec. VIII are indeed unlikely to succeed.

o Determine whether high microwave transmittance can be attained in ionic conductors.

The last goal was added near the end of the investigation. These goals were attained, as discussed in the appropriate sections and summarized in the abstract.

II. DIELECTRIC CONSTANT, REFRACTIVE INDEX, SURFACE REFLECTANCE, AND RESONANT FREQUENCIES

In subsequent sections we consider the dielectric constant, refractive index, and surface reflectance for phonon modes and plasma modes. Before considering these properties for specific systems, the following generally useful expressions are given for the convenience of the reader and for later use.

The index of refraction $n = n_r + i\kappa$ is related to the the dielectric constant $\varepsilon = \varepsilon_r + i\varepsilon_i$ by the simple square relation $n = \varepsilon^2$, where both n and ε are complex quantities. Only the case of magnetic permeability $\mu = 1$ is considered here. The real and imaginary parts are related by the expressions

$$\varepsilon_r = n_r^2 - \kappa^2, \tag{2.1}$$

$$\varepsilon_i = 2n_r\kappa, \tag{2.2}$$

$$n_r = (1/2)^{1/2}[(\varepsilon_r^2 + \varepsilon_i^2)^{1/2} + \varepsilon_r]^{1/2}, \tag{2.3}$$

$$\kappa = (1/2)^{1/2}[(\varepsilon_r^2 + \varepsilon_i^2)^{1/2} - \varepsilon_r]^{1/2}. \tag{2.4}$$

For $\varepsilon_i << \varepsilon_r$, Eqs. (2.3) and (2.4) reduce to

$$n_r \simeq \varepsilon_r^{1/2}, \qquad \text{for } \varepsilon_i << \varepsilon_r, \tag{2.5}$$

$$\kappa \simeq \varepsilon_i/2\varepsilon_r^{1/2}, \qquad \text{for } \varepsilon_i \ll \varepsilon_r. \tag{2.6}$$

The reflectance is

$$R = |(n - 1)/(n + 1)|$$

$$=[(n_r - 1)^2 + \kappa^2]/[(n_r + 1)^2 + \kappa^2]. \tag{2.7}$$

For the first condition, $n_r = 1$, for low reflectance, Eq. (2.7) becomes

$$R = \kappa^2/(4 + \kappa^2), \qquad \text{for } n_r = 1, \tag{2.8}$$

For the second condition, $\kappa \ll 2$, for low reflectance, Eq. (2.8) becomes

$$R \simeq \kappa^2/4, \qquad \text{for } n_r = 1 \text{ and } \kappa \ll 2. \tag{2.9}$$

This important result shows that the imaginary part κ of the refractive index must be small (much less than 2) in order to attain the desired low reflectance. These general conditions for low reflectance are displayed for later use

$$n_r = 1, \quad \text{and } \kappa \ll 2, \qquad \text{low-R conditions}. \tag{2.10}$$

Criterion on how low κ and the specific loss parameters must be for specific systems are developed in Sec. VI.

By using Eqs. (2.1) and (2.2), the low-reflectance conditions in Eq.

(2.10) can be written as

$$\varepsilon_r = 1, \qquad \varepsilon_i << 4, \qquad \text{low-R conditions.} \tag{2.11}$$

Equations (2.11) are the low-reflectance conditions in terms of the dielectric constant. Both n_r and ε_r are approximately equal to one and both κ and ε_i are small for low reflectance.

The resonant frequencies of a lossless system are the frequencies at which the system oscillates in the absence of an externally applied driving force. Thus the resonant frequencies are found by setting the real part of the dielectric constant equal to zero

$$\varepsilon_r = 0, \qquad \text{resonant-frequency condition,} \tag{2.12}$$

because the dielectric constant is the response function of the system.

frequency -- that is, the damping frequency -- of the free carriers, which are the conduction-band electrons or the valence-band holes. The room-temperature electron damping frequencies of the highest quality semiconductors usually are intrinsic, being determined by electron-phonon collisions. As the temperature is decreased, the electron-phonon collision rate decreases. At low temperatures, the extrinsic process of scattering of the electrons by impurities can determine the electron damping frequency.

The value of this damping frequency γ can be obtained from either the value of the mobility μ or the electrical conductivity σ. The following expressions for the mobility and the electrical conductivity are useful

$$\mu = e/\gamma m_{fc} \tag{6.1a}$$

and

$$\sigma = n_{fc} e_{fc}{}^{2}/m_{fc}\gamma. \tag{6.1b}$$

It is more convenient to obtain the value of γ from the mobility because only the values of μ and the electron effective mass m_{fc} are required; whereas, the electron density n_{fc} is also required in order to obtain the value of γ from the conductivity.

The highest mobility observed in a semiconductor is 5×10^{6} cm^2/volt-s (1.5×10^{9} cm^2/statvolt-s) for electrons in lead teluride at 4 K. The corresponding electron effective mass m_{fc} is $0.024m$, where m is the mass of the free electron. With these values of μ and m_{fc}, the expression γ =

VI. HIGH TRANSMITTANCE FROM LOW-FREQUENCY ELECTRON PLASMA MODES

In this section it is shown that the damping of low-frequency plasma modes is so great that they cannot be utilized to attain the low reflectance goal of Sec. V at room temperature.

In Sec. V it was shown that the operating frequency in Hz must be greater than the plasmon-damping frequency γ times 1.2 [or 0.38] in order to attain a reflectance of $R = 0.01$ [or 0.1] (20 dB less [or 10 db less] than that of a perfect reflector -- $R = 1$) or less. (As in the previous sections, the values in brackets are for the case of $R = 0.1$.) In particular, the frequency ν_{Rmn} at which the surface reflectance is minimum must satisfy Eq. (5.9). Unfortunately, there are no materials that have a sufficiently low loss for this criterion in Eq. (5.9) to be satisfied at room temperature for microwave and millimeter frequencies of current interest. Furthermore, material-improvement programs could not lower the losses because they are intrinsic, as discused below. Finally, operating at the low temperature of 4 K would lower the loss sufficiently to allow operation at frequencies greater than 18 GHz [or 6 GHz] for lead teluride, which has the greatest known mobility.

The damping frequencies of systems are usually strongly frequency dependent. Unfortunately, the damping frequency γ for solid-state plasmas are relatively independent of frequency. Thus, a damping frequency that is tolerably small in the infrared region can be unacceptably large in the microwave or millimeter region.

The damping frequency of solid-state plasmons is just the relaxation

Setting $\omega = \omega_{Rmn}$ (the operating frequency) form Eq. (2.20) in Eq. (2.17b) gives

$$\varepsilon_i = (\varepsilon_\infty - 1)\gamma/\omega_{Rmn} \tag{5.7}$$

Substituing ε_i from Eq. (5.7) into Eq. (5.4) gives

$$\omega_{Rmn} \geq (\varepsilon_\infty - 1)\gamma/0.40 \; [\text{or } (\varepsilon_\infty - 1)\gamma/1.26], \tag{5.8}$$

or

$$\nu_{Rmn} \geq 0.40(\varepsilon_\infty - 1)\gamma \; [\text{ or } 0.13(\varepsilon_\infty - 1)\gamma]$$

$$\geq 1.2\gamma \; [\text{or } 0.38\gamma], \qquad \text{for } \varepsilon_\infty = 4, \tag{5.9}$$

where ν's are frequencies in Hz and ω's are in radians per second (s^{-1}). The value of $\varepsilon_\infty = 4$ was chosen according to Eq. (2.16). This criterion in Eq. (5.9) is used in the following section in the discussion of plasma modes.

$$R \simeq \kappa^2/4, \qquad \text{for } n_r = 1 \text{ and } \kappa \ll 2. \tag{5.2}$$

Equations (5.1) and (5.2) give

$$\kappa < 0.2 \text{ [or 0.63]}, \qquad \text{criteria for high surface transmittance.}$$

(5.3)

Similarly, Eqs. (5.3) and (2.6) with ${\varepsilon_r}^{1/2} = 1$ give

$$\varepsilon_i < 0.4 \text{ [or 1.26]}, \qquad \text{criterion for high surface transmittance.} \tag{5.4}$$

as the criterion in terms of the imaginary part of the dielectric constant.

These values of κ or ε_i correspond to relatively high losses, not to ultra-low losses. For example, the loss tangent

$$\tan\delta = \varepsilon_i/\varepsilon_r \tag{5.5}$$

corresponding to Eq. (5.4) and $\varepsilon_r = 1$ are

$$\tan\delta < 0.40 \text{ [or 1.26]}, \tag{5.6}$$

which correspond to rather large losses.

Next consider the loss factor γ for a plasma. The value of γ corresponding to $\varepsilon_i < 0.4$ [or 1.26] in Eq. (5.4) is obtained as follows:

V. HIGH-TRANSMISSION CRITERIA

In this section, criteria are developed for high surface transmission of general systems and low-frequency plasmas. The criterion for low-frequency (soft) phonons is simple to develop, but is not included because soft phonons are not useful in the curent program, as discussed in Sec. VII.

Since this study is not related to a specific system, there is no specific system goal. In order to be concrete, the criterion for high surface transmission is chosen as

$$R = 0.01 \text{ [or } 0.1], \qquad \text{criteria for high surface transmittance,} \quad (5.1)$$

where R is the surface reflectance. The surface reflectance is the reflectance at the interface between a vacuum and the material. To be more specific, it is the reflectance of a semiinfinite medium in contact with vacuum. This value of reflectance, $R = 0.01$ [or 0.1], corresponds to a surface transmittance of 0.99 [or 0.90], of course. It also corresponds to a 20 dB [or a 10 dB] reduction in the specular reflectance below the valve of $R = 1$ (for metals in the microwave region). The alternate goal of $R = 0.1$, which corresponds to the figures in brackets, is discussed briefly for plasmons in Sec. VI. The general results of the study are not sensitive to the value of R chosen. They are the same for $R = 0.1$ and $R = 0.01$, for example.

First consider the value of κ that corresponds to $R = 0.01$ [or 0.1] for an arbitrary system. For $n_r = 1$ and $\kappa \ll 2$, Eq. (2.9) gives

nonzero for ω greater than ω_{res} and is zero ω less than ω_{res}. The results of adding loss is shown in Fig. 6b.

Finally, the reflectance obtained from Eq. (2.7) is sketched in Fig. 7 for both $\gamma = 0$ and γ greater than 0. The figure shows the high reflectance in the region $\omega < \omega_{res}$ and the low reflectance (zero for $\gamma = 0$) at the frequency ω_{Rmn} at which $n_r = 1$. The value of the reflectance at $n_r = 1$ for nonzero γ is calculated in Sec. VI.

$$\omega_{Rmn}/\omega_{res} = [\varepsilon_{\infty mw}/(\varepsilon_{\infty mw} - 1)]^{1/2}, \qquad \text{for } \omega_p{}^2 \gg \gamma^2, \tag{4.8}$$

$$= 1.15, \qquad \text{for } \varepsilon_{\infty mw} = 4. \tag{4.9}$$

The minimum reflectance frequency is greater than the resonant frequency by 15 percent in this example.

The real and imaginary parts of ε form Eqs. (4.4) and (4.5) are sketched in Fig. 5a for the case $\gamma = 0$ and in Fig. 5b for nonzero γ. The corresponding results for the refractive index obtained from Eqs. (2.3) and (2.4) are sketched in Fig. 6 and discussed below. First consider the lossless case of $\gamma = 0$. The imaginary part of the the dielectric constant is zero at all frequencies, as seen in Eq.(4.5) with $\gamma = 0$. The real part of the dielectric constant is negative for ω less than ω_{res} and is positive for ω greater than ω_{res}, as seen in Figs. 5a and 5b. Thus, a lossless plasma is a perfect reflector (no propagating modes) for ω less than ω_{res} and the optical modes having ω greater than ω_{res} propagate without loss (κ - 0). These results are obtained explicitly from the reflectance and the refractive index below.

The results of adding loss is shown in Fig. 5b. Both ω_{res} and ω_{Rmn} are shifted to lower frequencies as γ increases, as seen in Eqs. (4.6) and (4.7). For nonzero γ, ε_r is finite at $\omega = 0$ and ε_i approaches infinity as ω approaches zero.

As discussed in Sec. III for the case of phonon modes, these results for the dielectric constant imply that κ is nonzero for ω less than ω_{res} and is zero for ω greater ω_{res} for $\gamma = 0$, as seen in Fig. 6a. Also, n_r is

region. A low value of $\varepsilon_{\infty mw}$ is therefore

$$\varepsilon_{\infty mw} = 4, \qquad \text{low value.} \tag{4.3}$$

Taking the real and imaginary parts of ε in Eq. (4.1) gives

$$\varepsilon_r = \varepsilon_{\infty mw} - \omega_p{}^2/(\omega^2 + \gamma^2) \tag{4.4}$$

and

$$\varepsilon_i = (\gamma\omega_p{}^2/\omega)/(\omega^2 + \gamma^2). \tag{4.5}$$

The resonant frequency is obtained by setting $\varepsilon_r = 0$ in Eq. (4.4) and solving for ω. This gives

$$\omega_{res} = (\omega_p{}^2/\varepsilon_{\infty mw} - \gamma^2)^{1/2}. \tag{4.6}$$

The frequency ω_{Rmn} at which the reflectance is zero for $\gamma = 0$ is obtained by setting $\varepsilon_r = 1$ in Eq. (4.4) and solving for ω. This gives

$$\omega_{Rmn} = [\omega_p{}^2/(\varepsilon_{\infty mw} - 1) - \gamma^2]^{1/2}. \tag{4.7}$$

Notice that ω_{Rmn} is obtained from ω_{res} by replacing $\varepsilon_{\infty mw}$ in Eq. (4.6) by $\varepsilon_{\infty mw} - 1$.

For $\omega_p{}^2/\varepsilon_{\infty mw} \gg \gamma^2$, the ratio of the two frequencies in Eqs. (4.6) and (4.7) is

IV. PLASMA DIELECTRIC CONSTANT, REFRACTIVE INDEX, SURFACE REFLECTANCE, AND RESONANT FREQUENCIES

In this section we consider the dielectric constant, refractive index, surface reflectance, and resonant frequencies for electron or hole (free-carrier) plasmas. The dielectric constant of a plasma is

$$\varepsilon = \varepsilon_{\infty mmw} - \omega_p^2/[\omega(\omega + i\gamma)], \tag{4.1}$$

where $\varepsilon_{\infty mmw}$ is the high-frequency limit of the dielectric constant,

$$\omega_p = (4\pi n_{fc} e_{fc}^2/m_{fc})^{1/2} \tag{4.2}$$

is the collisionless plasma frequency, which is discussed in Sec. VI, and γ is the plasma damping frequency. In Eq. (4.2), the subscripts "fc" indicate free carrier, n is the free-carrier density, and m is the free-carrier effective mass.

For plasmas with resonant frequencies in the microwave or millimeter-wave regions, the infinite-frequency limit $\varepsilon_{\infty mmw}$ is the limit of the frequency large with respect to the microwave or millimeter-wave resonant frequencies (but still small with respect to the infrared and electronic resonant frequencies). Specifically, the vibrational modes, having resonant frequencies in the infrared region, and the electronic modes (for both the valence and core electrons), having resonant frequencies in the visible or ultraviolet regions or at greater frequencies, contribute to $\varepsilon_{\infty mmw}$. Thus, $\varepsilon_{\infty mmw}$ here is ε_0 for the infrared

1. These frequency shifts are rather small for usual values of Γ.

As seen in Fig. 3b, the nonzero value of Γ removes the infinities in the real and imaginary parts of the refractive index that are shown in Fig. 3a. For nonzero Γ, the reflectance in the Reststrahlen region is no longer equal to 1, but it is still relatively large. For example, typical values are 80 to 90 percent for the alkali halides. The reflectance at the frequency ω_{Rmn} at which $n_r = 1$ is no longer equal to zero, but it can be small for small Γ.

The surface reflectance below, in, and above the reststrahl-reflection region is sketched as the solid curve in Fig. 4 for the case of $\Gamma = 0$ by using Eq. (2.7) with n_r and κ from Fig. 3a. The surface reflectance is zero for

$$\varepsilon_r = 1, \qquad \text{zero surface reflectance for } \Gamma = 0. \tag{3.8}$$

The root of Eq. (3.8) with ε_r given by Eq. (3.2) with $\Gamma = 0$ is

$$\omega_{Rmn} = [(\varepsilon_0 - 1)/(\varepsilon_\infty - 1)]^{1/2}\omega_0. \tag{3.9}$$

This zero-reflectance frequency, ω_{Rmn}, in Eq. (3.9) is the operating frequency for minimum surface reflectance. The minimum-reflectance frequency ω_{Rmn} is greater than the longitudinal-optical frequency,

$$\omega_{Rmn} > \omega_{LO}. \tag{3.10}$$

This inequality precludes the possibility of obtaining high transmittance in the microwave or millimeter regions, as discussed in Sec. VIII.

Next consider the effects of nonzero Γ, which is the case of real materials, of course. The effects of nonzero Γ on the dielectric constant, refractive index, and surface reflectance are illustrated schematically in Figs. 2b, 3b, and 4, respectively. Adding the nonzero value of Γ has the following effects: As shown schematically in Fig. 2b, it removes the infinities in ε_r that are seen in Fig. 2a and it makes ε_i nonzero and peaked at frequency ω_0. It also shifts the frequencies at which $\varepsilon_r = 0$ and

of the transverse-optical phonon having wavevector $k = 0$. The second resonant-frequency root of Eq. (3.4), at the high-frequency crossing of $\varepsilon_r = 0$, is the frequency

$$\omega_{LO} = (\varepsilon_0/\varepsilon_\infty)^{1/2}\omega_0 \tag{3.6}$$

of the longitudinal-optical phonon having wavevector $k = 0$.

Consider the refractive index in the three regions $\omega < \omega_0$, $\omega_0 < \omega < \omega_{LO}$, and $\omega > \omega_{LO}$, still for the case of $\Gamma = 0$. Equation (3.3) with $\Gamma = 0$ shows that $\varepsilon_i = 0$, and Eqs. (2.1) and (2.2) show that

$$n_r = \varepsilon_r^{1/2}. \tag{3.7}$$

For frequencies lower than ω_0 and frequencies greater than ω_{LO}, ε_r is positive, as seen in Fig. 2a. Thus, Eq. (3.7) shows that the refractive index is purely real for the case of $\Gamma = 0$, as sketched in Fig. 3a. The optical modes therefore propagate without loss for $\omega < \omega_0$ and for $\omega > \omega_{LO}$.

For frequencies between these two resonant frequencies, the real part of the dielectric constant is negative. Thus, n is purely imaginary according to Eq. (3.7), as sketched in Fig. 3a. This purely imaginary refractive index means that there are no propagating modes in the material and that incident radiation having a frequency on this region between the two resonance frequencies is totally reflected for this case of $\Gamma = 0$. This region $\omega_0 < \omega < \omega_{LO}$ of total reflectance for $\Gamma = 0$ is the Reststrahlen reflection region.

$$\varepsilon_i = 2n_r\kappa$$

$$= [(\varepsilon_0 - \varepsilon_\infty)\omega_0^2\omega\Gamma]/[(\omega_0^2 - \omega^2)^2 + \omega^2\Gamma^2]. \qquad (3.3)$$

These dispersion relations, as the frequency dependence of the optical constants is called, in Eqs. (3.2) and (3.3) are sketched as functions of frequency in Fig. 2. The strong frequency dependence of Γ is formally neglected in this figure and in all figures below.

First consider the case of no loss, that is, $\Gamma = 0$. In the a part of Fig. 2, ε_r and ε_i are sketched for this case of $\Gamma = 0$. The imaginary part of the dielectric constant, ε_i, is equal to 0 for all frequencies, as seen from Eq. (3.2) with $\Gamma = 0$. For $\omega < \omega_0$, the real part of the dielectric constant, ε_r, increases monotonically with increasing frequency from ε_0 at $\omega = 0$ to ε_r approaching infinity as δ approaches zero, where $\omega = \omega_0 - \delta$. For $\omega > \omega_0$, ε_r increases monotonically with increasing frequency, starting from the limit of negative infinity for $\omega = \omega_0 + \delta$ as δ approaches zero and approaching ε_∞ as ω approaches infinity.

The resonant frequencies are the roots of the equation

$$\varepsilon_r = 0, \qquad \text{resonant-frequency condition} \qquad (3.4)$$

in general, as discussed in Sec. II. There are two roots of Eq. (3.4) with ε_r given by Eq. (3.2) and $\Gamma = 0$, as seen in Fig. 2a. The first root, which is the low-frequency crossing of $\varepsilon_r = 0$, gives the frequency

$$\omega_{TO} = \omega_0 \qquad (3.5)$$

III. PHONON DIELECTRIC CONSTANT, REFRACTIVE INDEX, SURFACE REFLECTANCE, AND RESONANT FREQUENCIES

In this section we consider the dielectric constant, refractive index, surface reflectance, and resonant frequencies of a material, such as an alkali halide, that has a single infrared-active phonon mode (at normal incidence). The dielectric constant is

$$\varepsilon = \varepsilon_\infty + (\varepsilon_0 - \varepsilon_\infty)\omega_0^2/[\omega_0^2 - \omega^2 - i\omega\Gamma], \tag{3.1}$$

where ε_∞ and ε_0 are the dielectric constants in the limits of infinite frequency and zero frequency, respectively, ω_0 is the characteristic frequency, and Γ is the damping constant, which is strongly frequency dependent. The infinite-frequency dielectric constant ε_∞ is the contribution from the valence and core electrons. For negligible loss, ε_∞ is the square of the refractive index in the visible region, roughly speaking.

Using Eqs. (2.1) and (2.2) and taking the real and imaginary parts of Eq. (3.1) gives

$$\begin{aligned}\varepsilon_r &= n_r^2(1 + \kappa^2/n_r^2) \\ &= \varepsilon_\infty + [(\varepsilon_0 - \varepsilon_\infty)\omega_0^2(\omega_0^2 - \omega^2)]/[(\omega_0^2 - \omega^2)^2 + \omega^2\Gamma^2]\end{aligned} \tag{3.2}$$

$e/m_{fc}\mu$ from Eq. (6.1a) gives $\gamma = 1.5 \times 10^{10}\ s^{-1}$. The low-loss criterion in Eq. (5.9) with $\varepsilon_\infty = 4$ from Eq. (2.16) gives

$$\nu \geq 18 \text{ GHz [or 6 GHz]}, \qquad \text{for PbTe at 4 K.} \tag{6.2}$$

Thus, even for operation at 4 K using PbTe, which has the greatest known mobility, the frequency still must be greater than approximately 18 GHz [or 6 GHz].

At room temperature the mobilities and corresponding loss frequencies are much greater than at low temperatures. The geatest known room-temperature mobility is $7.7 \times 10^4\ cm^2$/volt-s for indium intiminide. With $m_{fc} = 0.015m$, Eq. (6.1) gives $\gamma = 1.5 \times 10^{12}\ s^{-1}$. The criterion for low loss in Eq. (5.9) gives

$$\nu \geq = 1{,}800 \text{ GHz [or 6.00 GHz]}, \qquad \text{for InSb at 300 K.} \tag{6.3}$$

These frequencies are considerably greater than the frequencies of current interest, which are in the microwave region. Thus, there is no material having sufficiently low loss to allow room-temperature operation in the microwave or millimeter-wave regions of interest.

In order to make the minimum-reflectance frequency

$$\omega_{Rmn} = \omega_p/(\varepsilon_{\infty mw} - 1)^{1/2} \tag{6.4}$$

(from Eq. (4.7) with γ negligibly samll) small, either the plasma frequency must be small or the dielectric constant $\varepsilon_{\infty mw}$ must be extremely large.

Since there is no known way to make $\varepsilon_{\infty mw}$ sufficiently large, consider small values of the plasma frequency ω_p in Eq. (4.2). Solving Eqs. (4.2) and (6.4) for the free-carrier density gives

$$n_{fc} = \omega_{Rmn}{}^2 m_{fc}(\varepsilon_\infty - 1)/4\pi e_{fc}{}^2. \tag{6.5}$$

For a frequency of 30 GHz, $\varepsilon_\infty = 4$, and m_{fc} equal to the free-electron mass, Eq. (6.4) gives $n_{fc} = 3 \times 10^{13}\ \mathrm{cm}^{-3}$. This is of course an extremely small concentration (parts per billion). If electron-plasma systems are considered further, the practicality of attaining practical materials having such low electron concentration must be addressed.

VII. ABSENCE OF HIGH MICROWAVE TRANSMITTANCE FROM LOW-FREQUENCY PHONON MODES

In this section it will be shown that any one of several reasons is sufficient to show that soft- (low-frequency-) phonon modes are not useful as high-transmittance modes in the microwave and millimeter-wave regions. The background information available on soft phonon modes is extensive and is reviewed in many articles and textbooks, including <u>Introduction to Solid State Physics</u> by Charles Kittel.[3]

First, even if the resonant frequency ω_0 were in the microwave or millimeter-wave region, the frequency ω_{Rmx} at which the reflectance is minimum would still be in the inf~~a~~rred region. The resonant frequency ω_0 of the transverse-optical phonon having k = 0 in a solid usually is in the infrared region, rather than in the microwave or millimeter-wave regions. However, in some materials the frequency of the k = 0 transverse-optical phonon approaches zero at a certain temperature. This temperature is near room temperature in some materials. The zero-frequency mode is associated with a ferroelectric transition in such materials as barium titinate.

Physically, the low frequency is a result of a low restoring force in an oscillation of an ion. For example, in barium titinate the titanium ion is in the center site of a body-centered-cubic lattice. The restoring force for displacements along a (100) direction is small. In fact, at the ferroelectric-transition temperature, the titanium ion spontaneously displaces to a position that is not in the center of the cell. The energy of the ion as a function of the displacement is sketched schematically in Fig. 8a for the nonferroelectric phase and in Fig. 8b for the ferroelectric

phase.

The restoring force at equilibrium ($x = 0$ in the (a) part of the figure and $x = x_d$ in (b)) is proportional to the second derivative d^2E/dx^2 of the energy E with respect to the displacement x. The restoring force in Fig. 8a is small because the curvature is small. That is, the curve is relative flat at $x = 0$. The anharmonic terms (deviations from $E \sim x^2$) are large in both Figs. 8a and 8b because E(x) deviated drastically from the harmonic form $E \sim x^2$. A harmonic curve is sketched as the dashed line in Fig. 8a for comparison.

When ω_0 is small, the static dielectric constant ε_0 is large. Physically, the force from a small electric field moves the titanium ion a long distance because only a small amount of energy is required, as seen in Fig. 8a. The large displacement corresponds to a large dipole moment, which means a large dielectric conatant.

The relation between the small ω_0 and large ε_0 can also be seen from the Lydanne-Sachs-Teller relation

$$\omega_0{}^2/\omega_{LO}{}^2 = \varepsilon_\infty/\varepsilon_0, \tag{7.1}$$

where ω_{LO} is the longitudinal-optical frequency. This equation shows directly that a small ω_0 corresponds to a large ε_0, provided that $\omega_{LO}{}^2$ or ε_∞ is not small. The experimental verification that the static dielectric constant ε_0 is large when ω_0 is small shows that ω_{LO} does not become small when ω_0 becomes small. Physically, ω_{LO} remains large because the electrical contribution to ω_{LO} (which is responsible for ω_{LO} being greater than ω_0) remains large even when ω_0 becomes small.

The frequency ω_{Rmn} at which the reflectance is minimum is greater than ω_{LO}, as seen in Fig. 4. Thus, the large value of ω_{LO} implies that ω_{Rmn} is large, even when ω_0 is small. This is the central reason that precludes the use of the low-frequency phonon modes in attaining high surface transmittance in the microwave and millimeter regions.

Even if the mininum-reflectance frequency ω_{Rmn} were near ω_0, the use of the low-frequency phonon modes in attaining high surface transmittance in the microwave and millimeter regions would be precluded by the great loss of the resonant mode near the ferroelectric transition temperature. The great loss is discussed below.

A final problem with trying to use soft-phonon modes to obtain resonant frequencies in the microwave or millimeter regions is that the temperature would have to be extremely close to the ferroelectric-transition temperature in order for ω_0 to be in the microwave or millimeter-wave region. The temperature would have to be controlled extremely well, and small variations of either the temperature or material properties over the material would inhomogeneously broaden the resonance line. That is, the resonant frequency would be different at different positions in the material.

In principle, the first problem, that of a large value of ω_{Rmn}, could be avoided if a material having zero effective ionic charge could be found. This is of course highly unlikely. But if such a material could be found, the electrical contribution to ω_{LO} would then be zero, and the frequencies of the transverse- and longitudinal-optical modes would be more nearly equal than in normal materials. The static dielectric constant ε_0 would remain small as ω_0 became small because the dipole moment would be zero,

even though the displacement became large, because the charge is zero. The charge induced by displacement, as well as the static charge, would have to be small. The low frequency ω_{LO} of the longitudinal-optical mode would be consistent with this low value of ε_0.

If the soft-phonon modes are considered for use in other applications, the following additional information should be considered. A study of the source of the great damping of the soft-phonon modes would be useful in order to verify that the damping is intrinsic and to determine and understand the dependence of the damping on the material parameters and the system parameters. The first reason for the great damping is expected to be the large anharmonic terms mentioned above. These large anharmonic terms give rise to strong phonon-phonon interactions, which give rise to great damping. That is, Γ is large.

In a study of this damping, the following must be taken into account. The dominant loss process in the microwave region is the two-phonon absorption process in which the lifetime broadening of the interacting phonons allows energy conservation.[3] The microwave field excites the transverse-optical mode having frequency ω_0. This excitation process usually is far off resonance for microwave fields because ω_0 is in the infrared region. That is, $\omega \ll \omega_0$. (The excitation process usually is far off resonance for frequencies in the infrared region also because the inequality $\omega \gg \omega_0$ is often, but not always, satisfied).

The damping of the ω_0 mode, when driven in the microwave region, usually is determined by the three-phonon process in which the transverse-optical mode is annihilated, a large-k-vector acoustic mode (having frequency ω_A) is annihilated, and a large-k-vector

transverse-optical mode (having frequency ω_T) is created.[4] The lifetime broadening of the ω_A and ω_T modes is ess~~i~~ential in order to conserve energy because $\omega_0 \neq \omega_T - \omega_A$ in general. With lifetime broadening of the ω_T and ω_A modes, energy is conserved in the three-phonon process only to within the lifetime-broadening width of the ω_T and ω_A modes.

VIII. OTHER TYPES OF MATERIALS AND MODES

A number of other materials and modes have been suggested as candidates for obtaining high surface transmittance. These include liquids, bulk and surface plasma modes in metals, electron-hole droplets, and free excitons. In this section it will be shown that none of these materials or modes can be used to obtain high surface transmittance.

Liquids can have resonances in the microwave region in general. However, the resonances are of the relaxation-oscillation type, as illustrated in Fig. 9 for water, rather than the resonance type, as illustrated schematically in Figs. 1 or 2. Thus, the real parts of the dielectric constant and index of refraction decrease monotonically as the frequency increases, rather than showing the resonance behavior that is required in order to obtain $n_r = 1$. This relaxation-oscillation characteristic is a fundamental property of liquids. There is no known way to make liquids have resonance oscillations, and it is highly unlikely that a way will be found.

The best known example is water. The absorption by food in microwave ovens is determined essentially by the absorption of water. The oscillations are so highly overdamped that the resonant frequency of liquid water is an order of magnitude lower than that of water vapor. The real and imaginary parts of the dielectric constant are shown in Fig. 9. The most important feature of these curves for the present investigation is the monotonic decrease in the real part of the dielectric constant with increasing frequency, rather than the resonance behavior in Figs. 1 or 2 that is required in order to obtain $n_r = 1$.

Bulk and surface plasma modes in metals are not useful in the microwave region because these modes have frequencies in the ultraviolet region.

Based on the work of Manenkov and coworkers,[5] it has been suggested that free excitons and electron-hole droplets should be considered as candidates for systems having $n_r = 1$. It will now be shown that free excitons and electron-hole droplets cannot be used to obtain $n_r = 1$.

Manenkov and coworkers[5] investigated excitons in semiconductors by measuring the microwave conduction of samples that were irradiated by both a laser and a high-power microwave source. A laser was used to generate carriers. The carriers were subsequently greatly heated by a high-power microwave source. The effects of the carriers and their heating was studied by measuring the microwave absorption with a second microwave source. The heating of the carriers by the high-power microwave source does not involve the resonant frequencies of the free excitons or electron-hole droplets.

The analysis of the results involved free carriers, free excitons, and electron-hole droplets. However, the microwaves were used only as a tool to study these phenomena. There are no resonance frequencies in the microwave region that can be used to obtain $n_r = 1$.

IX. TUNABILITY

In this section it is shown that it is impractical in practice, though possible in principle, to tune the frequency ω_{Rmn} at which the reflectance in minimum.

The frequency ω_{Rmn} of minimum reflectance for a plasma mode can be changed in principle by changing the density of the free carriers. Form Eqs. (4.7) and (4.2), the relation between the density of free carriers and the minimum-surface-reflectance frequency is

$$\omega_{Rmn}{}^2 = 4\pi n_{fc}e^2/m(\varepsilon_\infty - 1) - \gamma^2. \tag{9.1}$$

According to Eq. (9.1), ω_{Rmn} increases as n_{fc} increases. For negligible
γ^2, Eq. (9.1) gives

$$\omega_{Rmn} \sim n_{fc}{}^{1/2}, \qquad \text{for negligible } \gamma^2.$$

The number of free carriers can be increased by any of the following method:

(1) thermal excitation of carriers from low-lying levels into the conduction band or valence band,

(2) thermal excitation of carriers across the bandgap in small-bandgap materials,

(3) photoionization of carriers across the band gap, and

(4) photoionization of carriers form levels in the gap into the

conduction band or valence band.

All of these methods are impractical in most applications. Thermal excitation requires close control of the temperature, in some cases over large areas. Changing the temperature is a slow process. Differences in the temperature in different parts of the material causes inhomogeneous broadening. Photoionization requires irradiation by a laser or other source.

The value of ω_{Rmn} could also be tuned by tuning the value of ε_∞ according to Eq. (9.1). However, there is no known practical way of tuning the value of ε_∞.

Finally, the value of ω_{Rmn} could be changed by frequency pulling. For example, the plasma mode could be coupled to another mode and either the frequency of the other mode of the coupling between the modes changed. The resonant frequencies of coupled modes depend on the frequencies of both uncoupled modes and on the strength of the coupling constant. Although there is no known practical method of frequency-pulling tuning of plasma modes, the method is illustrated by the example of the coupling of the plasma mode to a phonon mode.

The dielectric constant of the plasmon and phonon is

$$\varepsilon(\omega) = \varepsilon_\infty + \Omega^2/[\omega_0{}^2 - \omega^2 - i\omega\Gamma(\omega)] - \omega_p{}^2/\omega(\omega + i\gamma) \tag{9.2}$$

Here ω_0 is the frequency of a lattice resonance (transverse-optical phonon), $\Omega^2 = (\varepsilon_0 - \varepsilon_\infty)\omega_0{}^2$ is proportional to the oscillator strength of the mode, γ is the plasma damping frequency, Γ is the phonon damping

frequency, and

$$\omega_p^2 = 4\pi n_{fc}e^2/m_{fc} \tag{9.3}$$

is the collisionless plasma frequency. Here n_{fc} is the density of the carriers and m_{fc} is the effective mass of the carriers. Finally, ε_∞ is the contribution to the dielectric constant from the electronic interband transitions. For present purposes, the frequency dependence of ε_∞ is neglected.

Such a system supports collective oscillations of longitudinal character. If we ignore losses ($\Gamma = \gamma = 0$), it is easy to show that the resonant frequencies of these modes occur at the frequencies for which $\varepsilon(\omega) = 0$. In the present example, there are two such modes, with frequencies $\omega_\pm$ given by

$$2\omega_\pm^2 = (\omega_0^2 + \Omega^2/\varepsilon_\infty + \omega_p^2/\varepsilon_\infty) \pm$$

$$[(\omega_0^2 + \Omega^2/\varepsilon_\infty + \omega_p^2/\varepsilon_\infty)^2 - 4\omega_0^2\omega_p^2/\varepsilon_\infty]^{1/2}. \tag{9.4}$$

At frequencies just <u>above</u> each collective-mode frequency, one finds the minimum-reflectance frequencies $\omega_{Rmn\pm}$ at which $\varepsilon(\omega) = 1$ by replacing the explicit ε_∞ by $\varepsilon_\infty = 1$. This gives

$$2\omega_{Rmn\pm}^2 = [\omega_0^2 + \Omega^2/(\varepsilon_\infty - 1) + \omega_p^2/(\varepsilon_\infty - 1)] \pm$$

$$\{[\omega_0^2 + \Omega^2/(\varepsilon_\infty - 1) + \omega_p^2/(\varepsilon_\infty - 1]^2 - 4\omega_0^2\omega_p^2/(\varepsilon_\infty - 1)\}^{1/2}$$

(9.5)

for which $\varepsilon(\omega) = 1$. Here the material is perfectly impedance matched to the vacuum, for this case of no losses. Thus, it is a perfect transmitter of the electromagnetic wave. When dissipation is introduced, the dielectric constant cannot be purely real, just as was the case for the individual uncoupled modes discussed above.

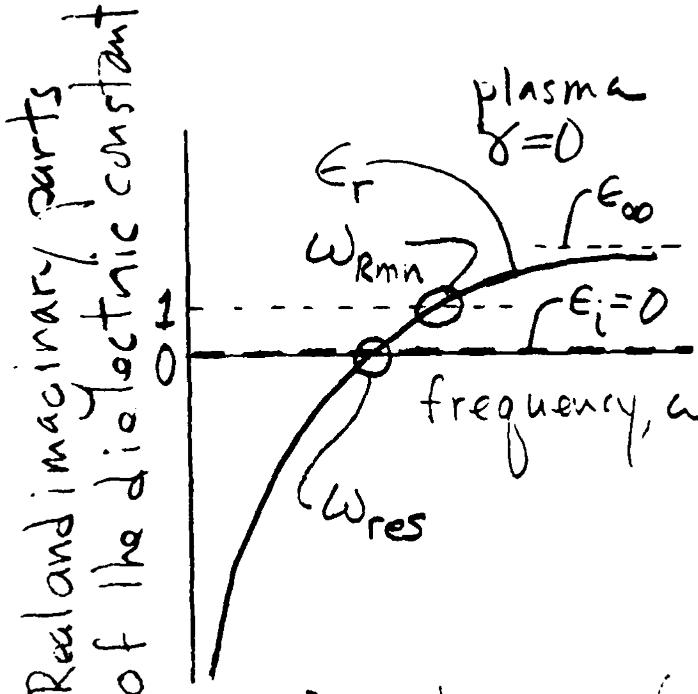
X. SUPER-IONIC-CONDUCTOR PLASMAS

Ion plasmas in super-ionic-conductor solids show promise of providing high microwave transmittance over a narrow band of frequencies. Since this effect was brought to our attention after the research on the program was completed, there was no time for a study of the effect. Only a cursory literature search was made, a number of experts in the field were contacted, and some thought was given to developing a model to explain the frequency dependence of the real and imaginary parts of the dielectric constant, ε_r and ε_i.

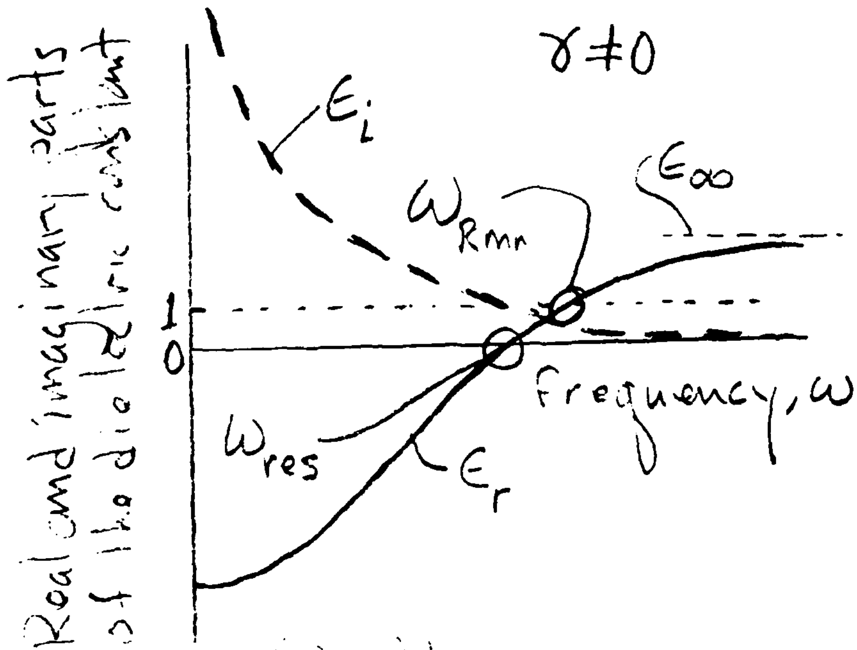
Super ionic conductors are believed to have the following properties: Some of the ions in the crystal, such as the sodium ions in $RbAg_4I_5$, are relatively free to move through the crystal at room temperature. The mobile ions must squeeze between the stationary ions in order to get from one site in the crystal to another. Thus there are energy barriers, of height W, that the ions must get over in going from one site to another.

It appears that there is no satisfactory explanation of the real and imaginary parts of the dielectric constant of super ionic conductors, but it is possible that a thorough literature search could uncover one. There is a vast literature on the <u>conductivity</u> of super ionic conductors, but no satisfactory discussions of plasma type behavior was found. The theoretical literature, starting with Rice and Roth[9] and including 57 references, was reviewed by Wong.[6] No satisfactory theory was discussed in that review.

Based on the observation of $\varepsilon_r = 1$ in the microwave region,[6] and preliminary estimates that the effective damping frequency may be

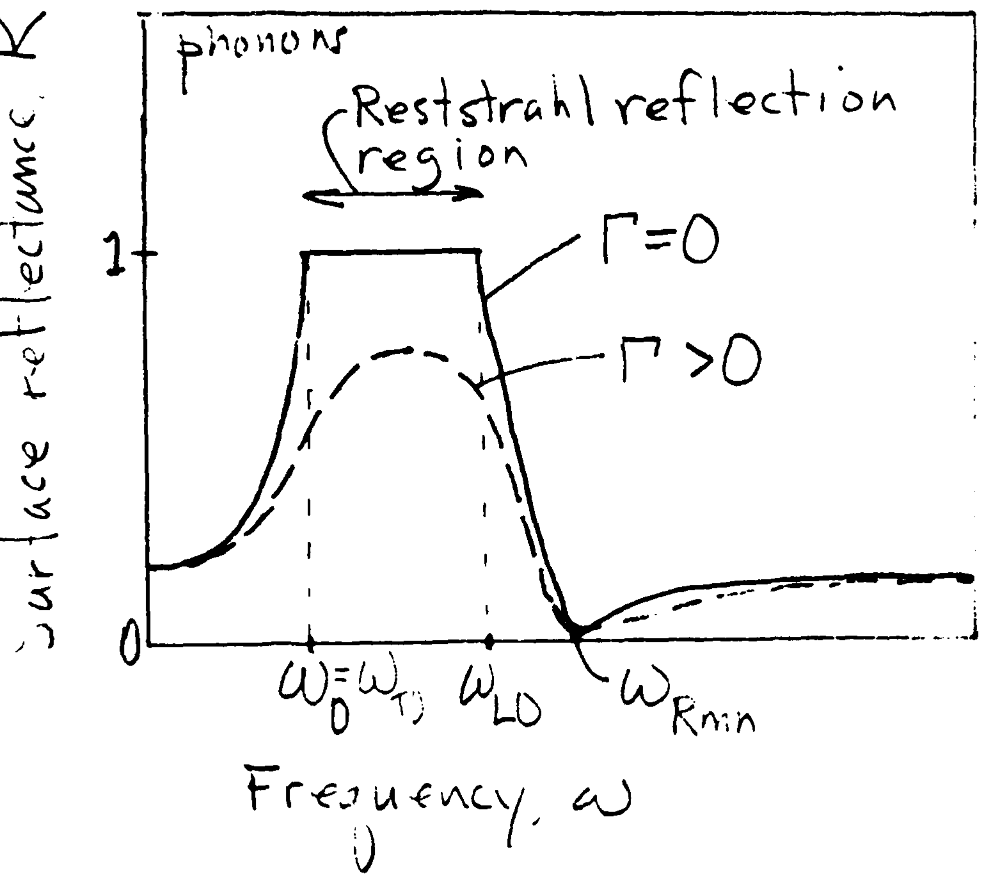


(a) no damping (collisionless)



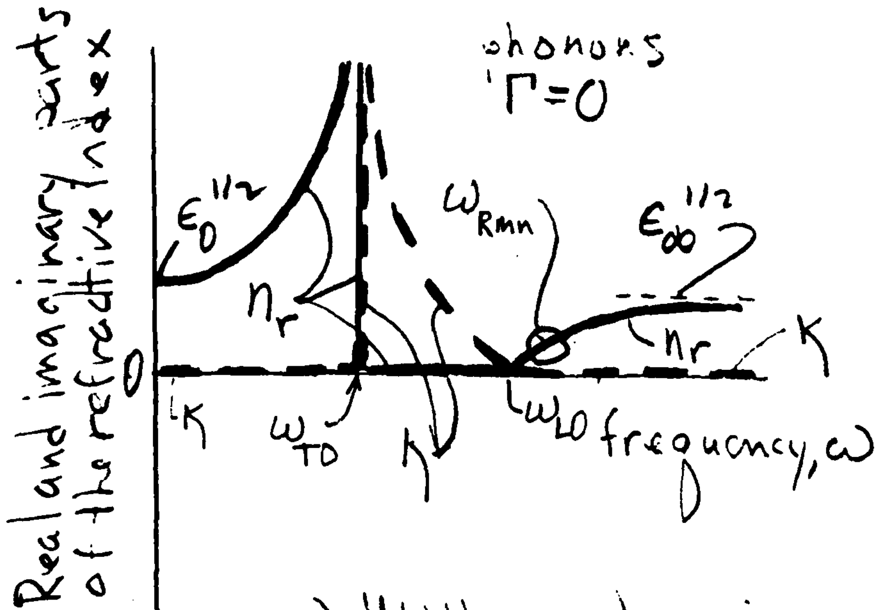
(b) With damping

Fig. 5

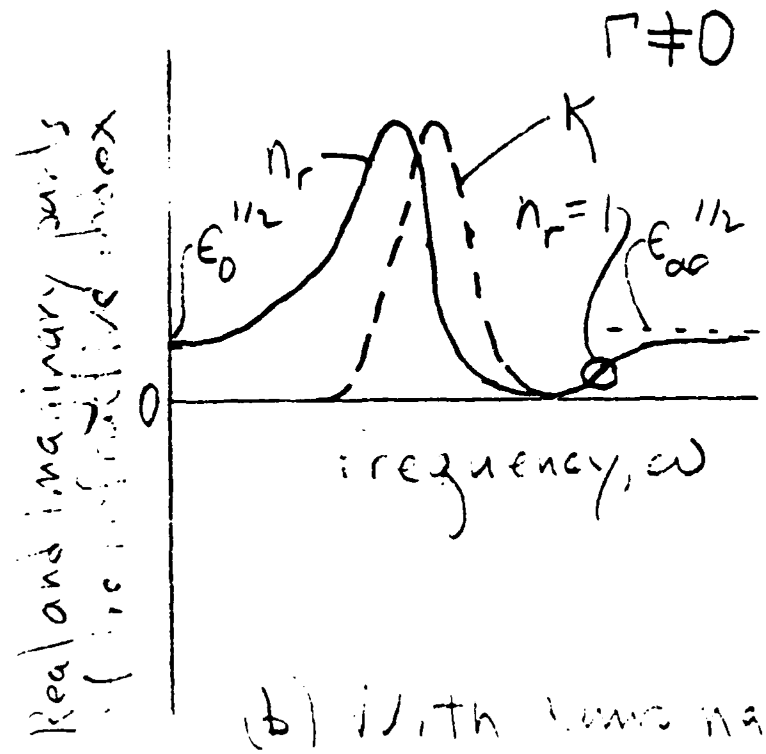


phonons
Reststrahl reflection region
$\Gamma = 0$
$\Gamma > 0$
1
0
$\omega_0 = \omega_{TO}$
ω_{LO}
ω_{Rmin}
Frequency, ω
Surface reflectance, R

Fig. 4

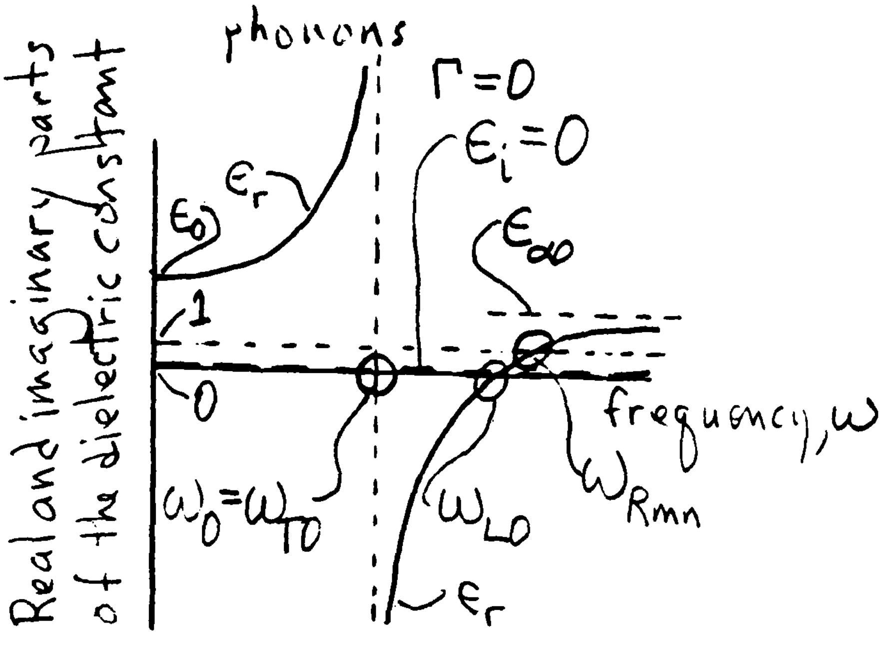


(a) With no damping

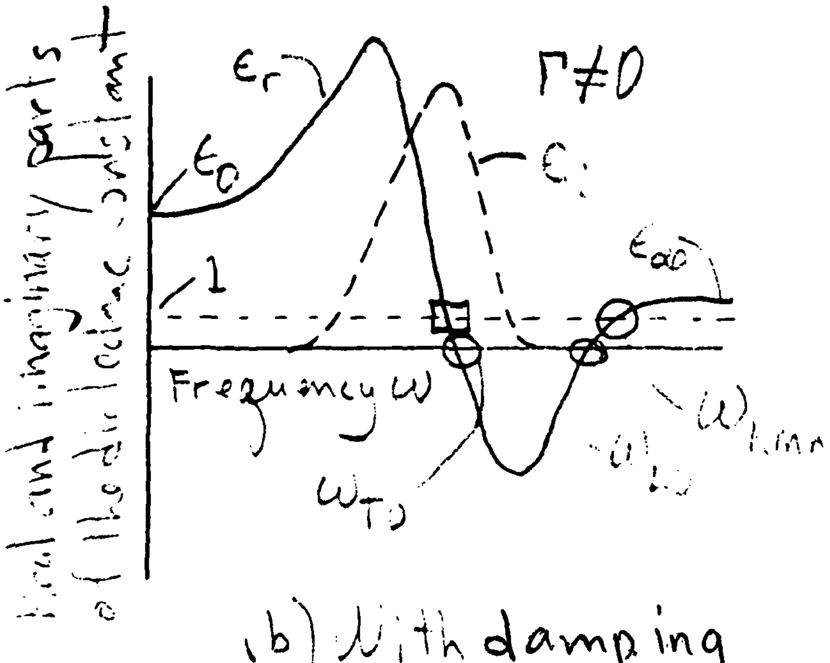


(b) With damping

Fig. 3



(a) With no damping



(b) With damping

Fig. 2

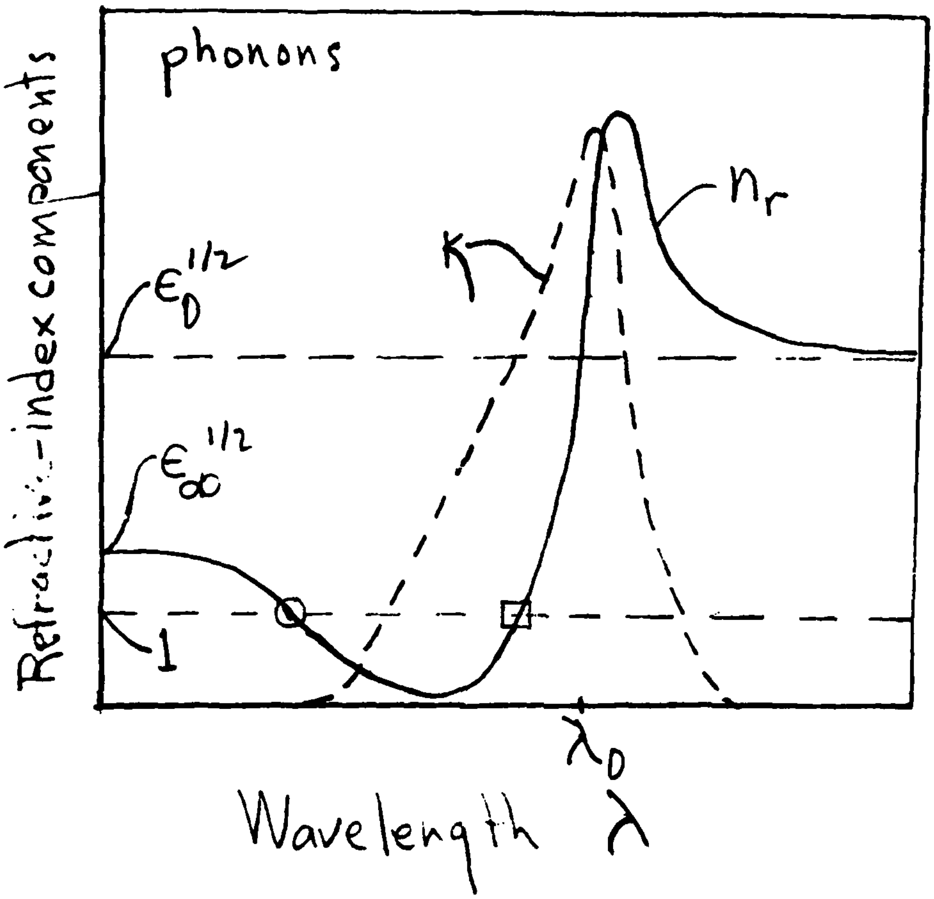

phonons
Refractive-index components
$\epsilon_D^{1/2}$
$\epsilon_\infty^{1/2}$
1
κ
n_r
λ_D
Wavelength λ

Fig. 1

showing the resonant frequency ω_{res} and the minimum-reflectance frequency ω_{Rmn}.

Fig. 7. Schematic illustration of the frequency dependence of the reflectance for plasmas, showing the resonant frequency ω_{res} and the minimum-reflectance frequency ω_{Rmn}.

Fig. 8. Schematic illustration of the displacement dependence of the energy of an ion in a ferroelectric material.

FIGURE CAPTIONS

Fig. 1. Schematic illustration of the wavelength dependence of the real and imaginary parts of the refractive index $n = n_r + i\kappa$ for phonons, showing the Christiansen short-wavelength (circled) and long wavelength at which $n_r = 1$ and the large value of n_r and κ near $\lambda = \lambda_0$.

Fig. 2. Schematic illustration of the frequency dependence of the real and imaginary parts of the dielectric constant $\varepsilon = \varepsilon_r + i\varepsilon_i$ for phonons, showing the resonant frequency (transverse-optical phonon frequency) ω_{TO}, the longitudinal-optical frequency ω_{LO}, and the minimum-reflectance frequency ω_{Rmn}.

Fig. 3. Schematic illustration of the frequency dependence of the real and imaginary parts of the refractive index $n = n_r + i\kappa$ for phonons, showing the resonant frequency (transverse-optical phonon frequency) ω_{TO}, the longitudinal-optical frequency ω_{LO}, and the minimum-reflectance frequency ω_{Rmn}.

Fig. 4. Schematic illustration of the frequency dependence of the reflectance for phonons, showing the resonant frequency (transverse-optical phonon frequency) ω_{TO}, the longitudinal-optical frequency ω_{LO}, and the minimum-reflectance frequency ω_{Rmn}.

Fig. 5. Schematic illustration of the frequency dependence of the real and imaginary parts of the dielectric constant $\varepsilon = \varepsilon_r + i\varepsilon_i$ for plasmas, showing the resonant frequency ω_{res} and the minimum-reflectance frequency ω_{Rmn}.

Fig. 6. Schematic illustration of the frequency dependence of the real and imaginary parts of the refractive index $n = n_r + i\kappa$ for plasmas,

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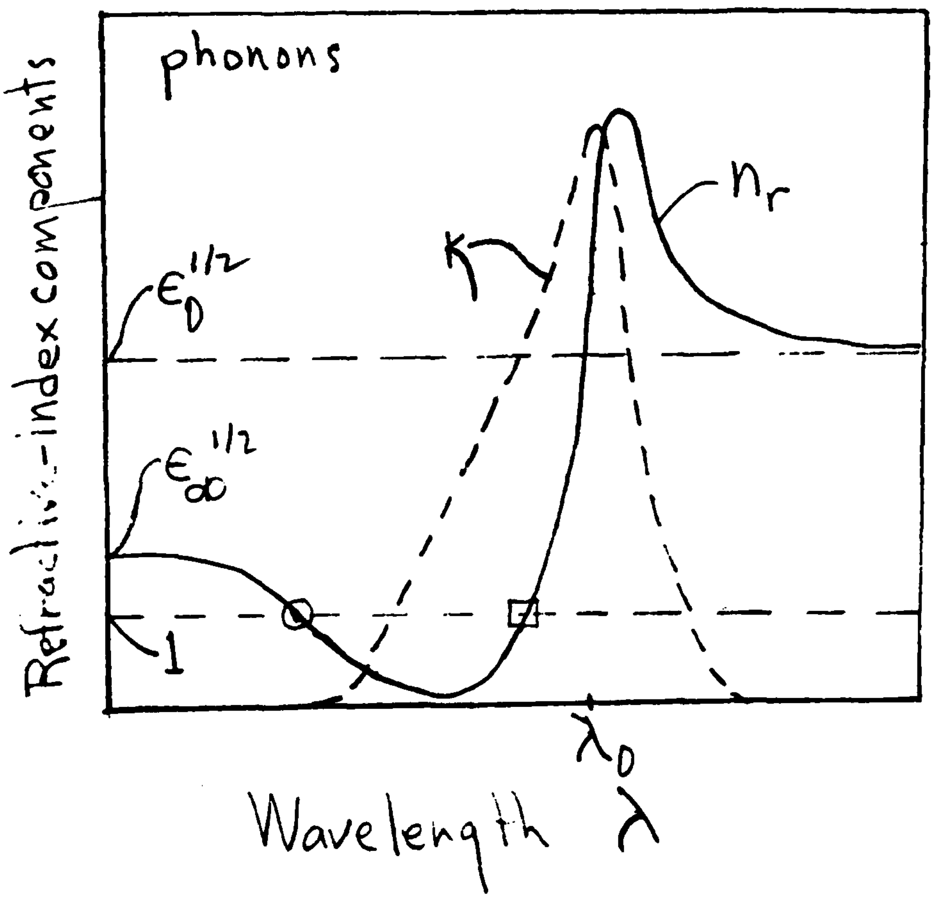
phonons
Refractive-index components
$\epsilon_0^{1/2}$
$\epsilon_\infty^{1/2}$
1
K
n_r
λ_0
Wavelength λ

Fig. 1

showing the resonant frequency ω_{res} and the minimum-reflectance frequency ω_{Rmn}.

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XI. ACKNOWLEDGMENTS

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sufficiemtly small, it is recommended that super ionic conductors be studied further.

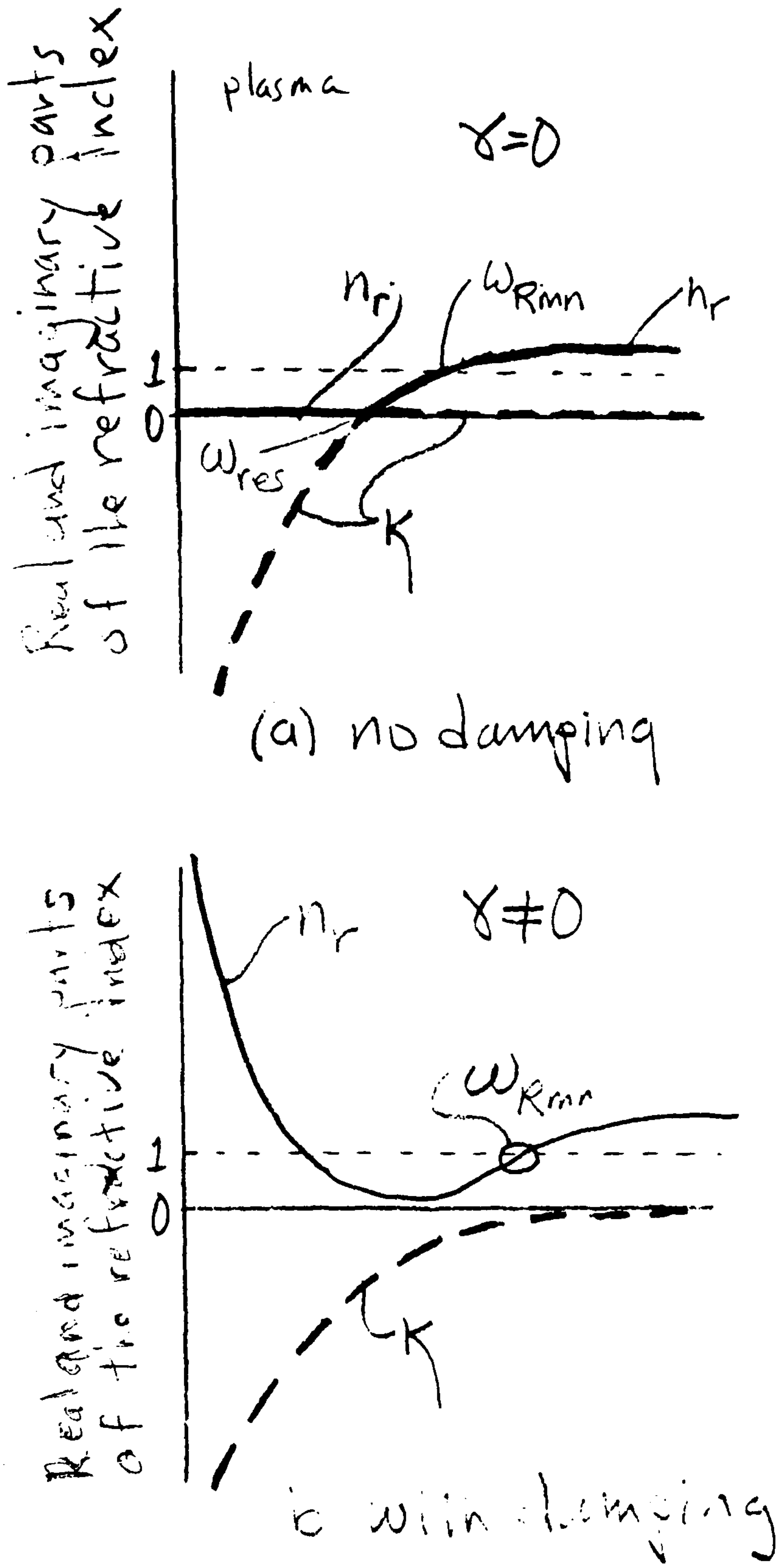

Real and imaginary parts of the refractive index
plasma
$\gamma = 0$
n_{ri}
ω_{Rmn}
n_r
1
0
ω_{res}
K
(a) no damping
n_r
$\gamma \neq 0$
ω_{Rmn}
1
0
τ_K

Fig. 6

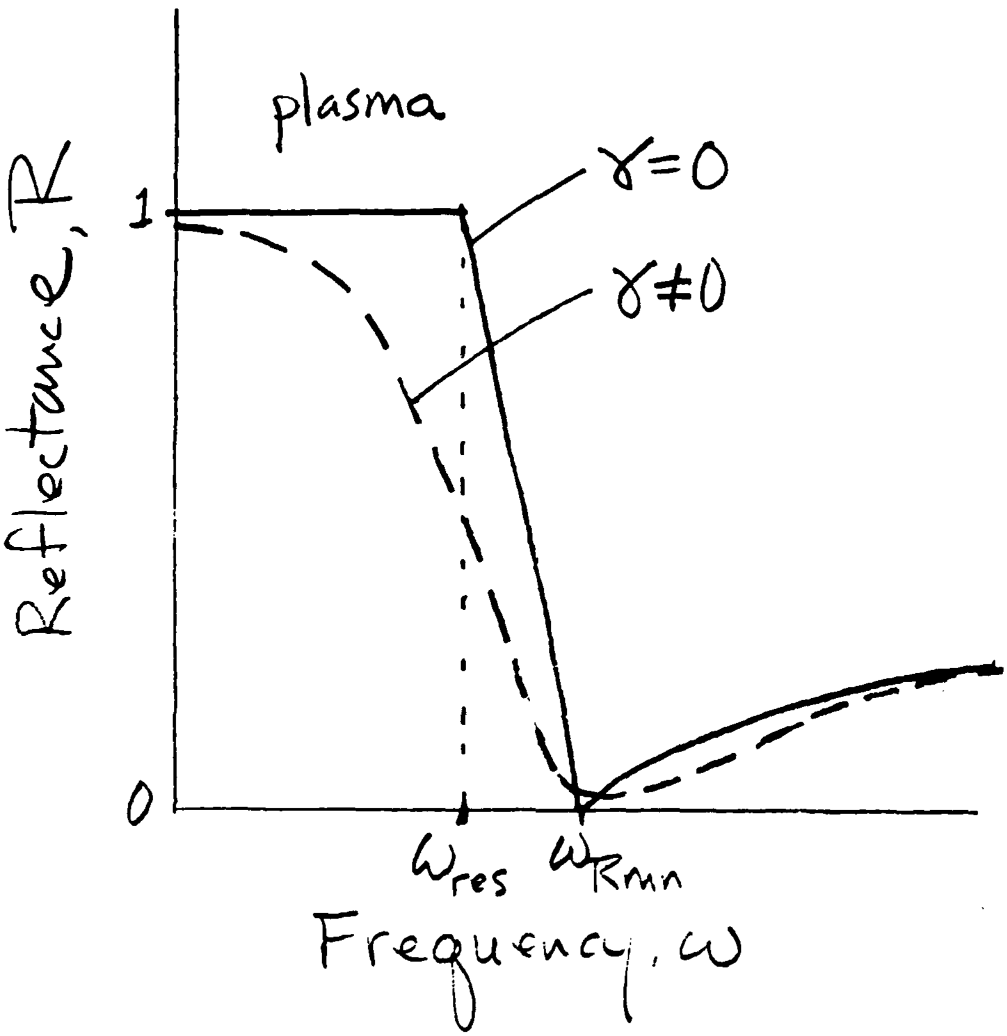
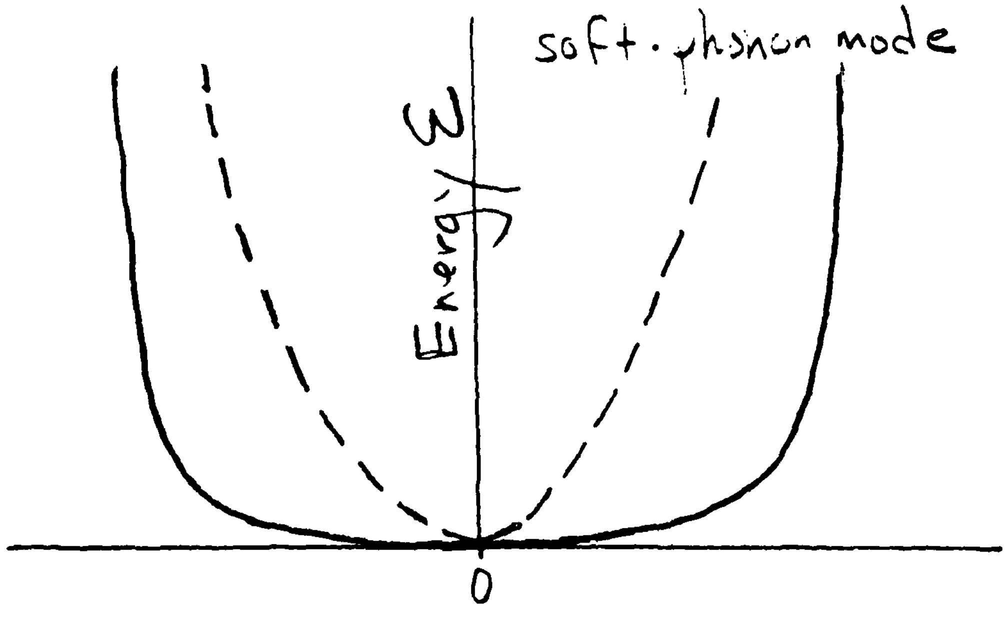
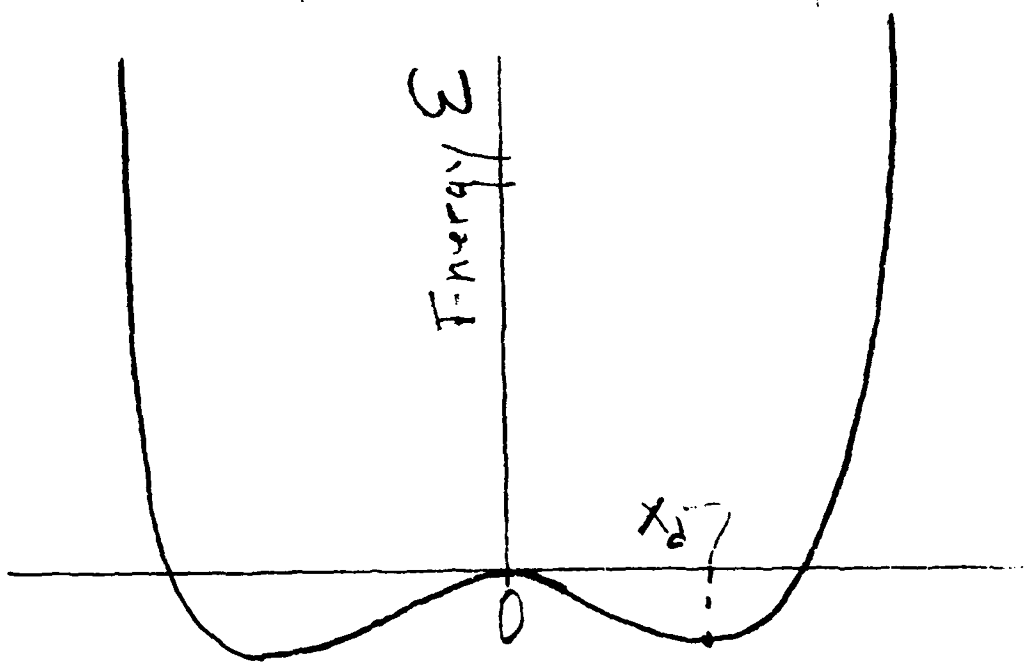

plasma
$\gamma=0$
$\gamma\neq0$
1
0
Reflectance, R
ω_{res}
ω_{Rmn}
Frequency, ω

Fig. 7



(a) Nonferroelectric phase



(b) Ferroelectric phase

Fig. 2

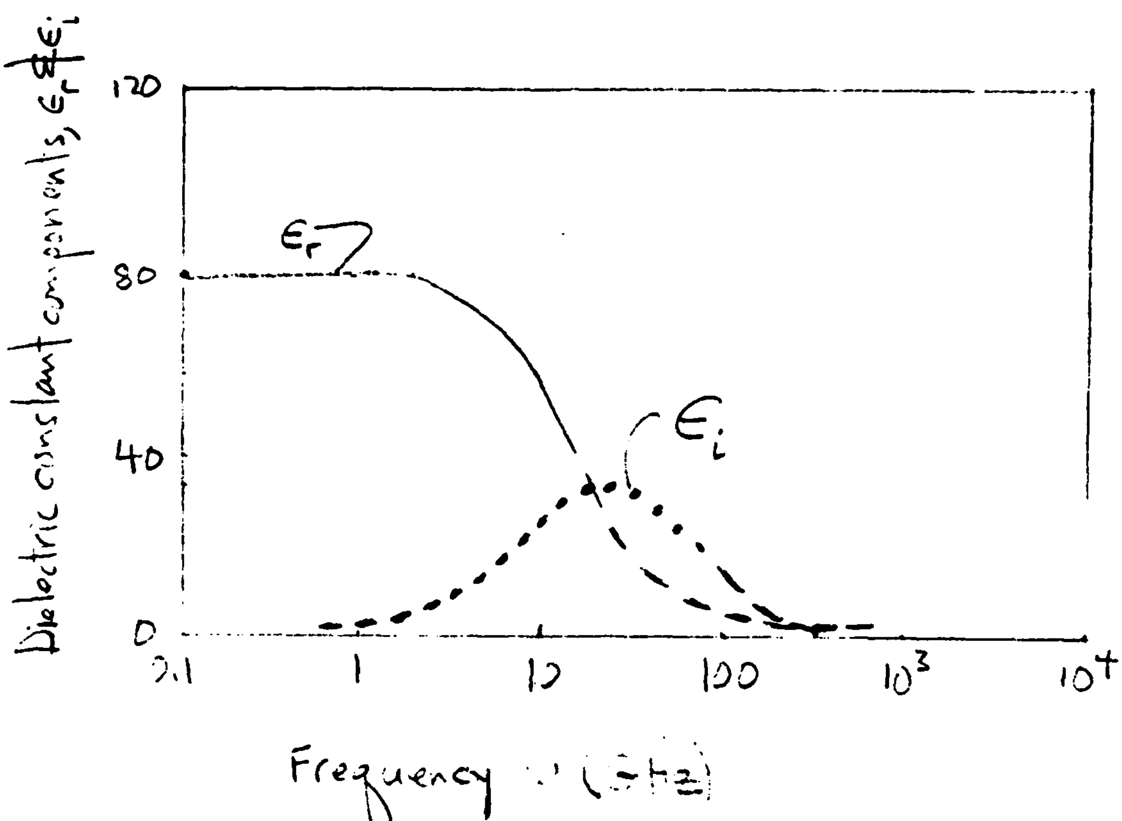


Fig. 9. Real and imaginary part of the dielectric constant of liquid water at room temperature, showing the monotonic decrease in ϵ_r. The dashed curves are extrapolations.

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